

Supersymmetric Axion-Neutrino Model with a Higgs Hybrid

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Abstract

In 2001, a supersymmetric model was proposed to relate the axion scale to that of neutrino mass seesaw. Whereas this scenario is realistic, the particles associated with this mechanism are either too heavy or too weakly coupled for them to be observed (other than the axion itself or perhaps the axino). A variation of that model is here proposed which allows significant mixing of the Higgs boson with a new singlet related to the saxion (the scalar partner of the pseudoscalar axion), rendering it possible to be observed at the Large Hadron Collider (LHC). With the addition of exotic color superfields, this also becomes a specific realization of how the production of such a Higgs hybrid may be suppressed or enhanced at the LHC, which is very relevant to ongoing experimental efforts to find the Higgs boson.

1 Introduction

Neutrino masses have been firmly established experimentally in recent years [1]. Any proposed model of particle interactions must now take this into account as a matter of course. Yet there are two theoretical questions which are often not considered in connection with neutrino mass. One is the hierarchy problem and the other is the strong CP problem. The first may be resolved by supersymmetry [2] and the second by the spontaneous breaking of a Peccei-Quinn symmetry, i.e. $U(1)_{PQ}$, which results in a very light pseudoscalar boson, the axion [3]. Whereas the existence of supersymmetry is being explored at the Large Hadron Collider (LHC), and should be discovered if its breaking scale is around 1 TeV, the ongoing experimental search for the axion is yet to reach definitive limits.

In 2001, a supersymmetric model was proposed [4] to relate the axion scale to the anchor scale of the seesaw mechanism for neutrino mass. The former is due to the vacuum expectation of a superfield in the range 10^9 to 10^{12} GeV and the latter is the mass of a singlet neutrino superfield which could be somewhat smaller because it is multiplied by a Yukawa coupling. The model is constructed with appropriate $U(1)_{PQ}$ charges for three singlet superfields, so that the breaking of $U(1)_{PQ}$ at the very high axion scale preserves the supersymmetry which breaks at the much lower TeV scale. This is then a comprehensive model of neutrino mass which is also intimately connected to the hierarchy and strong CP problems.

The three singlet superfields $\hat{S}_{0,1,2}$ of this model are the new additions to the Minimal Supersymmetric Standard Model (MSSM) with also three singlet neutrino superfields $\hat{N}_{1,2,3}^c$. The $U(1)_{PQ}$ symmetry is broken by $\langle S_{0,1} \rangle$, so that $N_{1,2,3}^c$ acquire large Majorana masses at the axion scale, but without breaking the supersymmetry. At the TeV scale of supersymmetry breaking, $\langle S_2 \rangle$ becomes nonzero and the μ term of the MSSM is generated. The axion,

axino, and saxion (the scalar partner of the axion) form the superfield which is a linear combination of $S_{0,1,2}$, whereas the other two linear combinations are very heavy. Both the axino and saxion have masses at or below the scale of supersymmetry breaking, but are very weakly coupled to the usual particles of the MSSM. As such, the LHC will not be very sensitive to the presence of these particles. A possible exception is the case where the axino is the lightest particle of odd R parity. In that case, it will contribute to the dark-matter relic density together with the axion, and the lightest MSSM neutralino will decay into it. As for the saxion of this model, there is no practical way to find it at all.

In this paper, a new singlet superfield \hat{S}_4 is added and the $U(1)_{PQ}$ charges are redefined so that the S_4 scalar field now mixes significantly with the MSSM neutral scalars. If S_4 also couples to heavy exotic color fermions, then this is a specific realization of the recently proposed idea [5] that a Higgs hybrid may have a suppressed or enhanced production from gluon fusion at the LHC, which is very relevant for the ongoing experimental effort to find the Higgs boson, even if the 125 GeV hint at the LHC is confirmed. More detailed studies of this basic idea have recently appeared [6, 7, 8].

In Sec. 2 the new model is defined. In Sec. 3 the new mass spectrum and the new particles with masses at or below the supersymmetry breaking scale are discussed. In Sec. 4 the possible new heavy exotic color particles are considered and the Higgs hybrid scenario is presented for either a suppression or enhancement of its production at the LHC. In Sec. 5 there are some concluding remarks.

2 Model

The superfields of this model with their $U(1)_{PQ}$ charges are listed below. In this notation, all fields are left-handed. The MSSM superfields are the usual $\hat{Q}, \hat{u}^c, \hat{d}^c, \hat{L}, \hat{e}^c, \hat{\phi}_1, \hat{\phi}_2$. The

superfield	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_{PQ}$
$\hat{Q} = (\hat{u}, \hat{d})$	$(3, 2, 1/6)$	-1
\hat{u}^c	$(3^*, 1, -2/3)$	-1
\hat{d}^c	$(3^*, 1, 1/3)$	-1
$\hat{L} = (\hat{\nu}, \hat{e})$	$(1, 2, -1/2)$	-3
\hat{e}^c	$(1, 1, 1)$	1
\hat{N}^c	$(1, 1, 0)$	1
$\hat{\phi}_1 = (\hat{\phi}_1^0, \hat{\phi}_1^-)$	$(1, 2, -1/2)$	2
$\hat{\phi}_2 = (\hat{\phi}_2^+, \hat{\phi}_2^0)$	$(1, 2, 1/2)$	2
\hat{S}_0	$(1, 1, 0)$	-2
\hat{S}_1	$(1, 1, 0)$	-1
\hat{S}_2	$(1, 1, 0)$	2
\hat{S}_4	$(1, 1, 0)$	-4
$\hat{\psi}$	$(6, 1, 1/3)$	2
$\hat{\psi}^c$	$(6^*, 1, -1/3)$	2

Table 1: $U(1)_{PQ}$ charges for all the superfields of this model.

new superfields are \hat{N}^c and $\hat{S}_{0,1,2,4}$. The color sextets $\hat{\psi}, \hat{\psi}^c$ are to be discussed in Sec. 4.

As a result, the superpotential of this model is given by

$$\begin{aligned}
\hat{W} = & m_2 \hat{S}_0 \hat{S}_2 + f_1 \hat{S}_1 \hat{S}_1 \hat{S}_2 + f_2 \hat{S}_2 \hat{S}_2 \hat{S}_4 + f_N \hat{S}_0 \hat{N}^c \hat{N}^c + f_4 \hat{S}_4 \hat{\phi}_1 \hat{\phi}_2 \\
& + h_d \hat{\phi}_1 \hat{Q} \hat{d}^c + h_u \hat{\phi}_2 \hat{Q} \hat{u}^c + h_e \hat{\phi}_1 \hat{L} \hat{e}^c + h_N \hat{\phi}_2 \hat{L} \hat{N}^c \\
& + h_1 \hat{\psi} \hat{u}^c \hat{d}^c + h_2 \hat{\psi}^c \hat{Q} \hat{Q} + h_4 \hat{S}_4 \hat{\psi} \hat{\psi}^c.
\end{aligned} \tag{1}$$

Note that multiplicative lepton number $(-1)^L$ and baryon number B are exactly conserved, with ψ being a diquark superfield having $B = 2/3$. The scalar potential coming from the first three terms of \hat{W} is

$$V = |m_2 S_2|^2 + |2f_1 S_1 S_2|^2 + |m_2 S_0 + f_1 S_1^2 + 2f_2 S_2 S_4|^2 + |f_2 S_2^2|^2. \tag{2}$$

Hence a solution which breaks $U(1)_{PQ}$ spontaneously while preserving supersymmetry is

$$\langle S_2 \rangle = \langle S_4 \rangle = 0, \quad m_2 \langle S_0 \rangle + f_1 \langle S_1 \rangle^2 = 0. \tag{3}$$

As shown in Ref. [4], as the supersymmetry is broken at the M_{SUSY} scale of about 1 TeV, this solution becomes

$$v_2 \sim v_4 \sim M_{SUSY}, \quad m_2 v_0 + f_1 v_1^2 \sim M_{SUSY}^2. \quad (4)$$

Of the four superfields, two remain massive at the m_2 scale, the other two have masses of order M_{SUSY} , except for the very light axion. The axion scale is $\sqrt{4v_0^2 + v_1^2} \sim m_2$. The heavy neutrino singlets have masses $f_N v_0$ and act as anchors in the usual Type I seesaw mechanism for very small Majorana masses of the active neutrinos. Variations of this basic idea is also possible for Type II, Type III, and radiative seesaw neutrino masses [9]. The supersymmetric $\mu \hat{\phi}_1 \hat{\phi}_2$ term is generated with $\mu = f_4 v_4$, and the scalar S_4 mixes with the usual neutral Higgs scalars of the MSSM. At the same time, the exotic color sextet quarks have masses $h_4 v_4$. Whereas the MSSM Higgs scalars couple to two gluons through the SM quarks, the S_4 scalar couples to two gluons through the sextet quarks.

3 New particles at the TeV Scale

The axion comes from a linear superposition of the angular fields θ_i of $S_i = (1/\sqrt{2})(v_i + \rho_i) \exp(i\theta_i/v_i)$ as well as $\phi_{1,2}^0 = (1/\sqrt{2})(v_{d,u} + \rho_{d,u}) \exp(i\theta_{d,u}/v_{d,u})$, i.e.

$$a = (-2v_0\theta_0 - v_1\theta_1 + 2v_2\theta_2 - 4v_4\theta_4 + 2v_d\theta_d + 2v_u\theta_u)/V, \quad (5)$$

where $V^2 = 4v_0^2 + v_1^2 + 4v_2^2 + 16v_4^2 + 4v_d^2 + 4v_u^2$. In the presence of electroweak symmetry breaking, the combination $\theta_d \cos \beta - \theta_u \sin \beta$, where $\tan \beta = v_u/v_d$, is absorbed by the Z boson. As a result, the electroweak component of the physical axion becomes $2 \sin 2\beta (\theta_d \sin \beta + \theta_u \cos \beta)$. The normalization V is corrected by changing $(v_d^2 + v_u^2)$ to $(v_d^2 + v_u^2) \sin^2 2\beta$. Since $v_{d,u} \sim 100$ GeV, $v_{2,4} \sim 1$ TeV, and $v_{0,1} \sim 10^9$ to 10^{12} GeV, the two massive superfields are roughly \hat{S}_2 and $(v_1 \hat{S}_0 - 2v_0 \hat{S}_1)/V$, thereby allowing the superfield containing the axion and \hat{S}_4 to have

components with masses of order M_{SUSY} . Now this model is constructed with \hat{S}_4 interacting with $\hat{\phi}_1\hat{\phi}_2$ and $\hat{\psi}\hat{\psi}^c$. The scalar S_4 will then mix with the scalar $\phi_{1,2}^0$, and so do their fermionic counterparts. Such is of course a very familiar scenario in supersymmetry, where a singlet superfield is added to the MSSM. Here it has an axion connection and may also couple to exotic quarks.

The usual 4×4 mass matrix for the neutralinos of the MSSM is now extended to an 8×8 mass matrix, spanning $(\tilde{B}, \tilde{W}_3, \tilde{\phi}_1^0, \tilde{\phi}_2^0, \tilde{S}_0, \tilde{S}_1, \tilde{S}_2, \tilde{S}_4)$:

$$\mathcal{M} = \begin{bmatrix} \tilde{m}_1 & 0 & -sm_3 & sm_4 & 0 & 0 & 0 & 0 \\ 0 & \tilde{m}_2 & cm_3 & -cm_4 & 0 & 0 & 0 & 0 \\ sm_3 & -cm_3 & 0 & f_4v_4 & 0 & 0 & 0 & f_4v_u \\ -sm_4 & cm_4 & f_4v_4 & 0 & 0 & 0 & 0 & f_4v_d \\ 0 & 0 & 0 & 0 & 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2f_1v_2 & 2f_1v_1 & 0 \\ 0 & 0 & 0 & 0 & m_2 & 2f_1v_1 & 2f_2v_4 & 2f_2v_2 \\ 0 & 0 & f_4v_u & f_4v_d & 0 & 0 & 2f_2v_2 & 0 \end{bmatrix}, \quad (6)$$

where $s = \sin \theta_W$, $c = \cos \theta_W$, $m_3 = M_Z \cos \beta$, $m_4 = M_Z \sin \beta$, with $\tan \beta = v_u/v_d$. Using $m_2 \simeq f_1v_1^2/v_0$, it is clear that \tilde{S}_2 combines with $(v_1\tilde{S}_0 - 2v_0\tilde{S}_1)/V$ to form a Dirac fermion of mass f_1v_1V/v_0 , and the axino is mostly $(2v_0\tilde{S}_0 + v_1\tilde{S}_1)/V$ with mass $2f_1v_2(4v_0^2/V^2)$. The singlino \tilde{S}_4 mixes with the MSSM neutralinos. If $v_4 \sim 1$ TeV, then its mass is approximately $-2f_4v_uv_d/v_4$ which is of order 10 GeV. If $v_4 \sim 100$ GeV, then it mixes significantly with the MSSM neutralinos and all are of order 100 GeV. In either case, it could be an important component of dark matter. If the axino is the lightest particle of odd $R \equiv (-1)^{3B+L+2j}$, then the decay of the lightest neutralino into the axino plus a Higgs boson (real or virtual) is very much suppressed and may be visible at the LHC as a displaced vertex or not at all.

As for the scalar sector, this scenario is very much like the NMSSM, where a singlet superfield is added [10] to the MSSM. However, there is no $\kappa\hat{S}_4\hat{S}_4\hat{S}_4$ term in the superpotential here. There are two 3×3 mass-squared matrices, one for the real parts of ϕ_1^0, ϕ_2^0, S_4 and

the other for the imaginary parts. The latter has one zero eigenvalue, corresponding to the would-be Goldstone boson for the longitudinal component of the Z boson. In the NMSSM, there would be another zero eigenvalue (axion) because $\kappa = 0$, but not so here because the axion is mostly not in S_4 , as explicitly stated already in Eq. (5). Significant mixing between the neutral Higgs bosons of the MSSM with S_4 is possible, and the lightest particle of this sector could very well be a Higgs hybrid, with a suppressed (or enhanced) coupling to two gluons as recently proposed [5], thus affecting the ongoing search for the Higgs boson at the LHC. Even if the 125 GeV hint at the LHC is confirmed, its production cross section times decay branching fraction into $\gamma\gamma$ for example may not be exactly as the SM predicts. If it is smaller or larger, then this scenario may be the answer especially if it is larger.

4 Color sextets

As Eq. (1) shows, the color sextet superfields $\hat{\psi}, \hat{\psi}^c$ of this model obtain their masses from $\langle S_4 \rangle = v_4$, just as $\hat{\phi}_{1,2}$. They should thus appear at the TeV scale. They also contribute to the S_4 -gluon-gluon one-loop amplitude, in analogy to the usual H -gluon-gluon one-loop amplitude which is dominated by the t quark. The Higgs hybrid, i.e. $H' = H \cos \theta - S_4 \sin \theta$, may then have a suppressed (or enhanced) coupling to two gluons, as recently proposed [5]. [The color factor for sextets is $5/2$ here, instead of 3 for the octets considered there.] This will affect its experimental production cross section at the LHC. Furthermore, since the color sextets also have electric charge, the $H' \rightarrow \gamma\gamma$ branching fraction is changed as well. At present, LEP and LHC data constrain the SM Higgs boson H to be between 115 and 130 GeV in mass, and there is a hint that it may be 125 GeV. If it is not discovered in this range, or discovered at a level, either above or below what is expected in the SM, this exotic model would be a possible explanation. Even if the SM Higgs boson is eventually confirmed, i.e. $\theta = 0$, the scalar S_4 may still be discovered through its gluon-gluon coupling at a higher

mass.

The presence of exotic particles in general has many phenomenological implications [11]. Here because of the $U(1)_{PQ}$ symmetry, both $(-1)^L$ and B are conserved. Hence proton decay as well as neutron-antineutron oscillations are forbidden. Since ψ couples to u and d quarks (and not d and d or u and u quarks), there are no tree-level contributions to $K^0 - \bar{K}^0$, $B^0 - \bar{B}^0$, $B_s^0 - \bar{B}_s^0$, or $D^0 - \bar{D}^0$ mixing. However, these mixings do occur in one-loop. Whereas they should not contribute much to $K^0 - \bar{K}^0$ mixing, they could have some nonnegligible effect on the others, especially $D^0 - \bar{D}^0$ [12]. They also contribute to QCD penguin digrams and may be important for observing CP violation beyond the SM in charm decays for example.

5 Concluding remarks

To have a comprehensive model of particle interactions, a supersymmetric extension of the standard model is considered with an $U(1)_{PQ}$ symmetry, which is spontaneously broken (thus solving the strong CP problem) at a high scale by a set of singlet superfields without breaking the supersymmetry. The neutrino singlet superfields also acquire mass at the same time, relating thus the seesaw mechanism for naturally small Majorana neutrino masses to the axion scale. The dark matter of the Universe may have two components, the axion which has even R parity, and the axino or neutralino which have odd R parity. All these were accomplished in a model proposed many years ago [4]. A new singlet superfield \hat{S}_4 is added here, which also couples to exotic color sextet diquarks, realizing thus the Higgs hybrid scenario proposed recently [5] which allows for deviations from the standard-model predictions of Higgs boson production and decay. As LHC data accumulate, this scenario will be tested and its parameters constrained.

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